CIPANP 2025

Sepehr Samiei

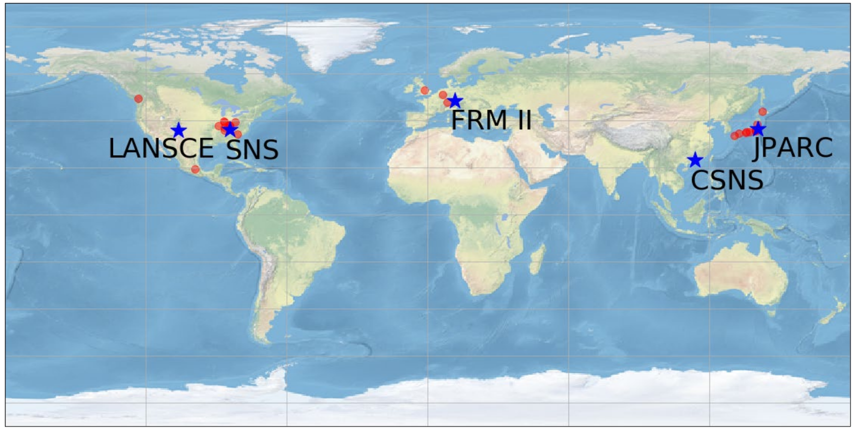
NOPTREX: Neutron Optics Parity and Time REversal eXperiment

NOPTREX/IRES Collaboration 6/7/2025

NOPTREX: C. Auton[16], E. Babcock[29], M. Barlow[30], L. Barron-Palos[27], L. Charon-Garcia[42], E. Chekmenev[32], A. Couture[20], C. Crawford[19], B. Crider[39], K. Dickerson[29], D. Eigelbach[20], S. Endoh[1,3], R. Fan[15,38], J. Fry[24], H. Fujioka[7], B. Goodson[22], V. Gudkov[17], C. Haddock[21], K. Hagino[11], H. Harada[3], P. Hautle[28], L. Hebenstiel[16], M. Hino[11], K. Hirota[1], I. Ide[1], M. Iinuma[6], H. Ikegami[10], T. Ino[4], R. Ishiguro[13], S. Ishimoto[4], K. Ishizaki[1], T. Iwata[9], P. Jahn[22], C. Jiang[18], W. Jiang[15], K. Kameda[7], S. Kawamura[1], G. Kim[14], A. Kimura[3], P. King[23], M. Kitaguchi[1], Y. Kiyanagi[1], J. Koga[2], H. Kohri[8], A. Komives[31], S. W. Lee[14], Q. Lu[15,38],G. Luan[34], M. Luxnat[16], T. Matsushita[1], M. McCrea[36], J. Mills[24], K. Mishima[4], Y. Miyachi[9], T. Momose[5], T. Morishima[1], T. Mulkey[45], Y. Niinomi[1], I. Novikov[25], J. O'Mahar[19], T. Okudaira[1], M. Okuizumi[1], K. Ogata[8], T. Oku[3], G. Otero[16], J. Palomino[39], S. Penttila[18], A. Perez-Martin[27], A. Petrilla[22], B. Plaster[19], X. Ruan[34], K. Sakai[3], S. Samiei[16], M. Sarsour[45] , D. Schaper[16], M. Scott[46], R. Shchepin[33] ,T. Shima[8], H. Shimizu[1], Z. Siraj[22], W. Snow[16], D. Spayde[35], H. Tada[1], J. Tang[37], Z. Tang[20], Y. Tani[7], S. Takada[2], Y. Takahashi[11], D. Takahaski[12], K. Taketani[8], A. Taninah[40], K. Tateishi[10], X. Tong[15], T. Uesaka[10], N. Vassilopoulos[15], M. Veillette[26], G. Visser[16], N. Wada[1], M. Wan[43], Y. Wang[19], D. Wei[41] , H. Wijerante[45], J. Winkelbauer[20], T. Yamamoto[1], Y. Yamagata[10], H. Yan[43], H. Yoshikawa[8], T. Yoshioka[2], M. Yosoi[8] , L. Zanini[44], M. Zhang[15,16], Q. Zhang[34]

IRES: D. Bishop[16], J. Britt[24], S. LeRose[19], N. Niemotka[35], N. Palley[46], L. Potts[25], E. Shipp[16], K. Swafford[24], J. Traywick[39], D. Waxley[26], M. Wilson[26], A. Winterman[19]

[1]Nagoya, [2]Kyushu, [3]JAEA, [4]KEK, [5]British Columbia, [6]Hiroshima, [7]Tokyo Inst. Tech., [8]Osaka, [9]Yamagata, [10]RIKEN, [11]Kyoto, [12]Ashikaga, [13]Japan Women's, [14]Kyungpook, [15]CSNS, [16]Indiana, [17]South Carolina, [18]ORNL, [19]Kentucky, [20]LANL, [21]Phase III Physics, [22]Southern Illinois, [23]Ohio, [24]Eastern Kentucky, [25]Western Kentucky, [26]Berea, [27]UNAM, [28]PSI, [29]Juelich, [30]Nottingham, [31]DePauw, [32]Wayne State, [33]SDSM&T, [34]CIAE, [35]Hendrix, [36]Manitoba, [37]USTC, [38]IHEP, [39]Mississippi, [40]LSU/Shreveport, [41]Tech. Inst. Phys. Chem., [42]TRIUMF, [43] Ningbo, [44] ESS, [45] Georgia State, [46]Centre



NOPTREX

IRES: International Research Experiences for Students

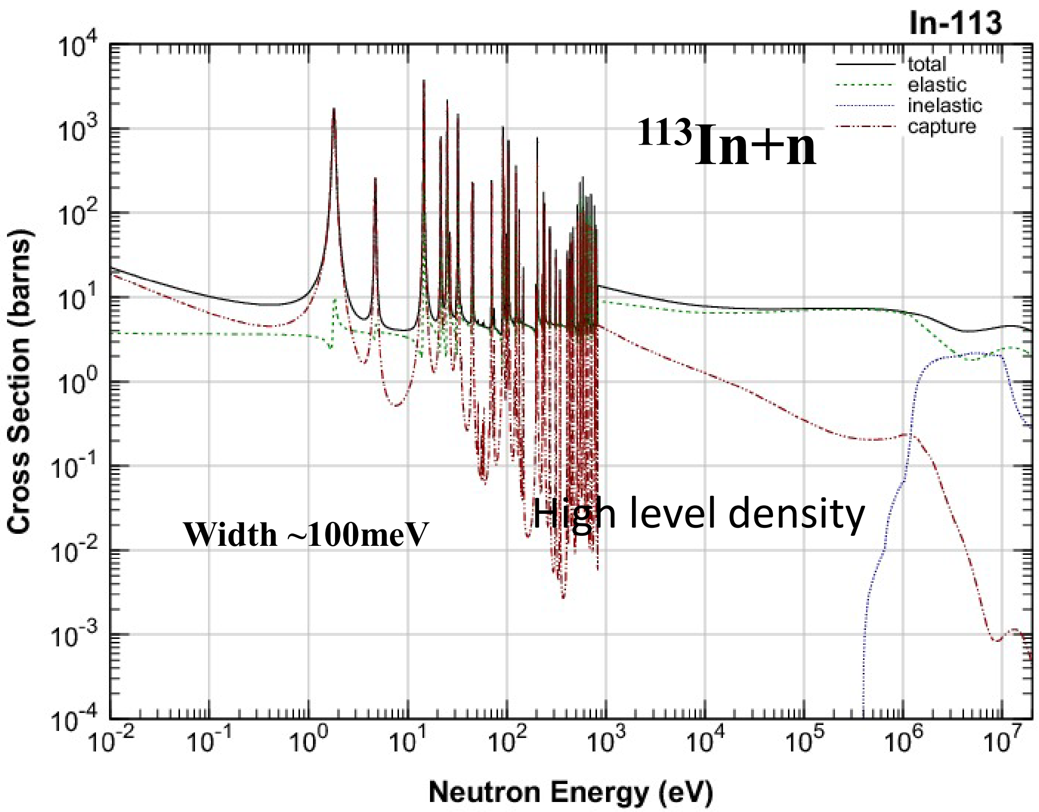
One experiment: Five neutron sources

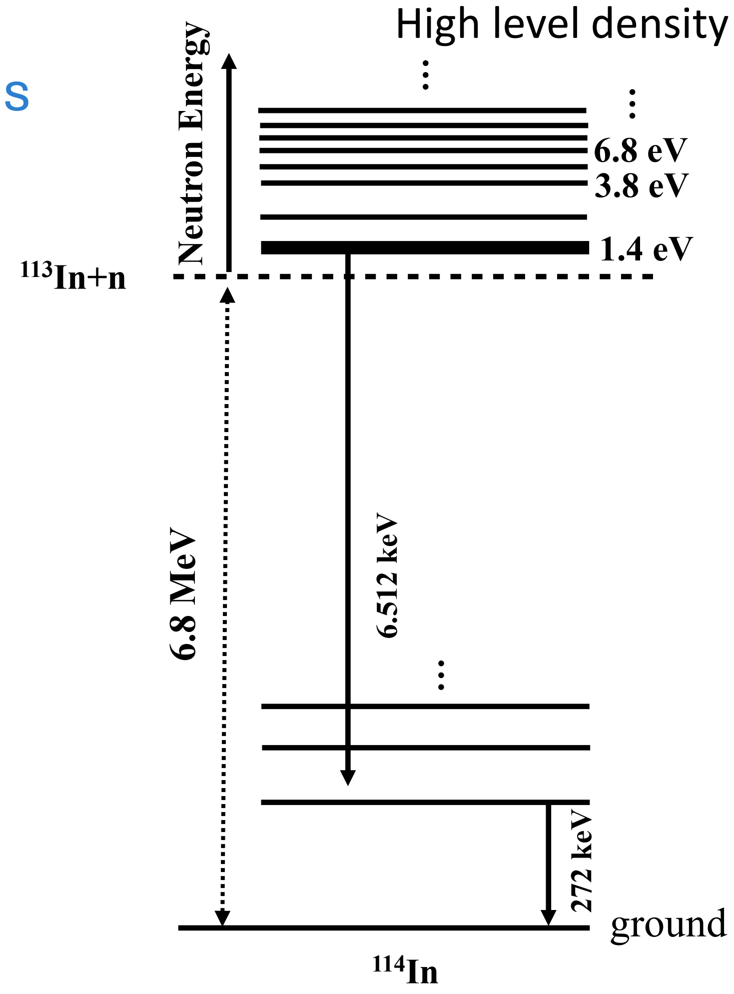
Neutron-Nucleus Resonances

dense set of resonances just above neutron separation energy

mainly L=0 resonances, but lots of L=1 resonances

P-odd interaction can mix L=0 and L=1 states





Three scientific goals of NOPTREX: Why Do IT?

(1) Understand P violation in heavy nuclei

-Quantify mean square weak matrix element $\langle M^2 \rangle$ in heavy nuclei

-Compare with statistical theory of P violation in heavy nuclei

(2) Search for P-odd/T-odd NN interaction

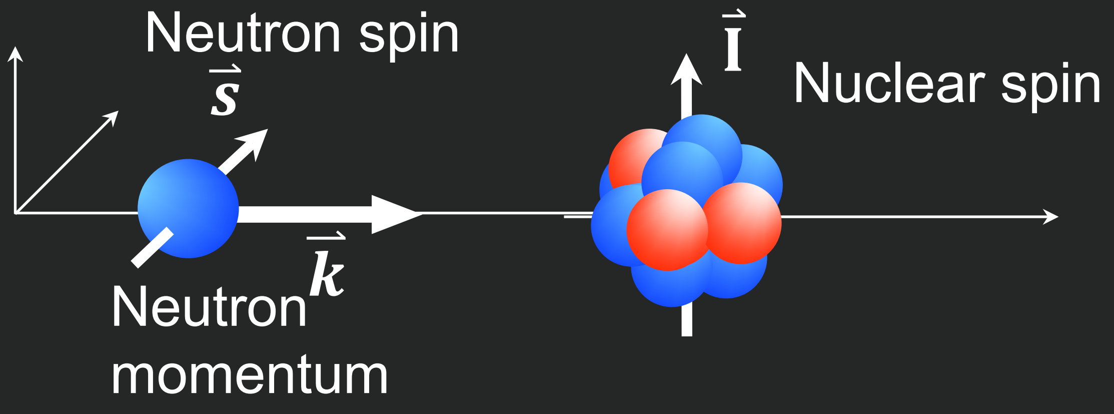
-Discover new source of P-odd/T-odd interaction

(3) Search for P-even/T-odd NN interaction

-Discover new source of P-even/T-odd interaction

-Aid interpretation of P-odd/T-odd electric dipole moment (EDM) searches

Neutron-Nucleus forward scattering amplitude



$$f = A + B(\vec{s}\cdot\vec{I}) + C(\vec{s}\cdot\vec{k}) + D(\vec{s}\cdot[\vec{k}\times\vec{I}]) + E(\vec{k}\cdot\vec{I}) + F(\vec{k}\cdot\vec{I})(\vec{s}\cdot[\vec{k}\times\vec{I}])$$

Elastic (zero angle scattering) scattering amplitude as scalar products of $\vec{s}$, $\vec{I}$, and $\vec{k}$:

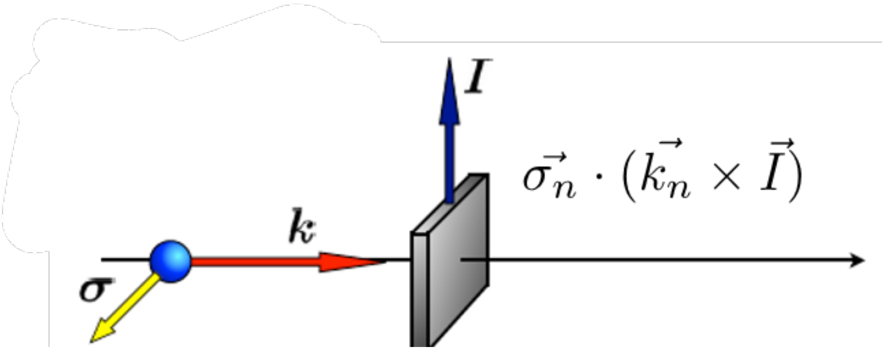
- A is dominated by (spin independent) strong interactions.
- B is from strong interaction spin-spin interactions.
- C & E come from parity-violating (P-odd) interactions.
- D comes from time- and -parity violating (P-odd, T-odd) interactions.
- F comes from T violating but parity-conserving (P-even, T-odd) interactions.

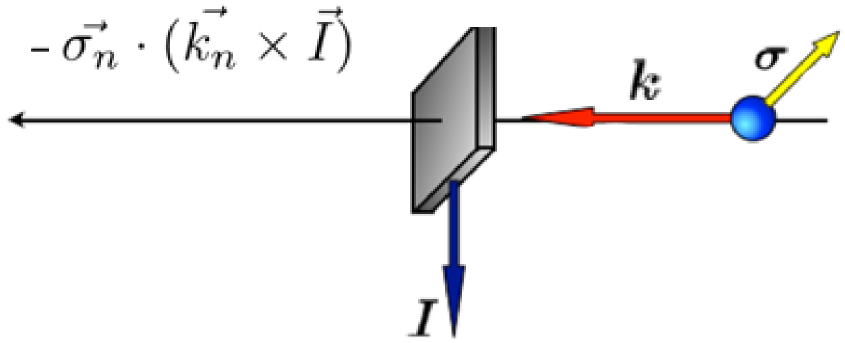
Beda and Skoy, “Current Status of Research on T Invariance in Neutron-Nuclear Reactions.”

Why C, D & F, Are Null Tests

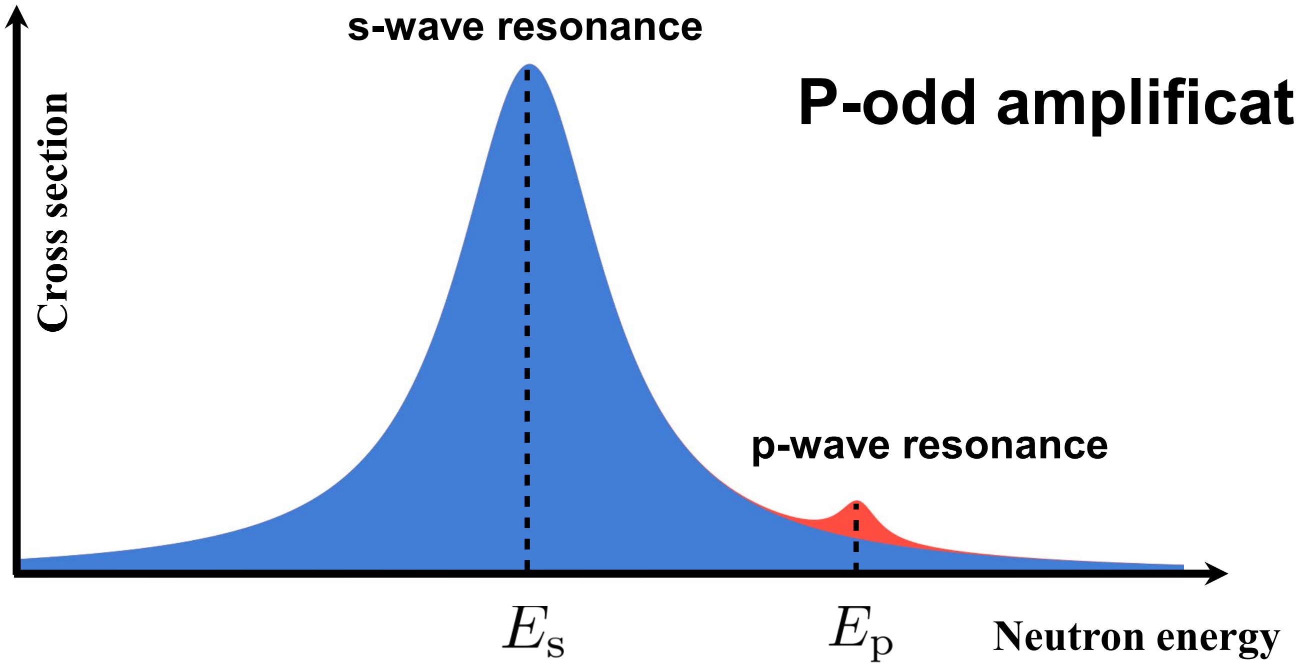
$$\sigma_{\text{tot}} = \frac{4\pi}{k}\,\mathrm{Im}\, f(\hat{\mathbf{k}}),$$

- For forward scattering initial and final state coincide, so any observable odd under P or T must vanish unless the corresponding symmetry is broken.
- The *difference* of total cross sections between two spin states therefore isolates exactly one coefficient in forward scattering amplitude using optical theorem.
- Ryndin theorem: In the absence of TRIV , swapping the incoming and outgoing spin–momentum configuration leaves the forward transmission **probability** unchanged. Any non-zero D,F is direct symmetry violation (Ryndin 1964, Gudkov & Bowman 2014).
- A null test for T: no "final state effects"





Enhancement of parity violation: mechanism



P-odd amplification in a p-wave resonance near a s-wave

$$H = \begin{pmatrix} E_s - i\Gamma_s/2 & v \\ v & E_p - i\Gamma_p/2 \end{pmatrix}$$

“Structural” enhancement: The weak mixing lets the large *s-*wave capture amplitude feed the tiny *p-*wave channel.

“Complexity/Dynamical” enhancement: in a nucleus excited by neutron capture, the interval Ep-Es between the chaotic compound states (resonances) of opposite parity is very small.

Theoretically, the enhancement is written as

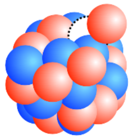
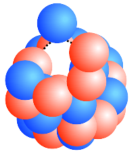
$$\frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{\Delta\sigma_{\mathrm{P}}}{2\sigma} = -\frac{2W}{E_{\mathrm{p}} - E_{\mathrm{s}}}\sqrt{\frac{\Gamma^{\mathrm{n}}_{\mathrm{s}}}{\Gamma^{\mathrm{n}}_{\mathrm{p}}}}\boxed{\sqrt{\frac{\Gamma^{\mathrm{n}}_{\mathrm{p},j=\frac{1}{2}}}{\Gamma^{\mathrm{n}}_{\mathrm{p}}}}}$$

Complexity Enhancement	Structural Enhancement	Partial neutron width j=1/2 component : χ
10^2 - 10^3	~ 10^3	Recently measured for ^{139}La!

Dynamical enhancement of Parity violation

s, p state are described by linear combination of one-hole one-particle state

$$|\mathrm{s}\rangle = \sum_i^N a_i |i\rangle\,, \quad |\mathrm{p}\rangle = \sum_j^N b_j |j\rangle \quad \to a_i \sim \frac{1}{\sqrt{N}}, \quad b_i \sim \frac{1}{\sqrt{N}}$$

$|\mathrm{s}\rangle =$  $|i\rangle +$  $|j\rangle + \ldots$

$$|W|^2 = \left|\langle \mathrm{s}|H_W|\mathrm{p}\rangle\right|^2 = \sum_{ij}^N \left(a_i b_j^* \langle \mathrm{i}|H_W|\mathrm{j}\rangle\right)^* \left(a_i b_j^* \langle \mathrm{i}|H_W|\mathrm{j}\rangle\right)$$

$$= \sum_i^N (a_i a_i^*)(b_i b_i^*)\left|\langle \mathrm{i}|H_W|\mathrm{j}\rangle\right|^2 + \sum_{i\neq j}^N (a_i a_j^*)\langle \mathrm{i}|H_W|\mathrm{j}\rangle^* (b_i b_j^*)\langle \mathrm{i}|H_W|\mathrm{j}\rangle$$

$$\sim \frac{1}{N}\frac{1}{N}\left|\langle \mathrm{i}|H_W|\mathrm{j}\rangle\right|^2 \times N$$

Random phase of $a_i, b_i \to 0$

Gauss Orthogonal ensemble in Random matrix

$$\to |W| \sim \frac{1}{\sqrt{N}}\left|\langle \mathrm{i}|H_W|\mathrm{j}\rangle\right|$$

Statistical nature of compound nucleus

$$\frac{|W|}{E_\mathrm{s} - E_\mathrm{p}} \sim \frac{\frac{1}{\sqrt{N}}\left|\langle \mathrm{i}|H_W|\mathrm{j}\rangle\right|}{\Gamma_{\mathrm{spr}}/N} = \sqrt{N}\boxed{\frac{\left|\langle \mathrm{i}|H_W|\mathrm{j}\rangle\right|}{\Gamma_{\mathrm{spr}}}}$$

P-violation in one particle state

Weak matrix element should depend on level density

Separation energy of one nucleon from ground state : $\Gamma_{\mathrm{spr}} \sim 10\ \mathrm{MeV}$

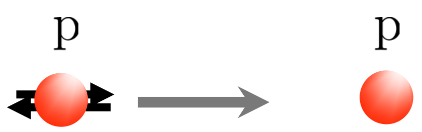
State density of compound resonance : $E_s - E_p \sim D \sim 100\ \mathrm{eV}$

→Number of components to express 100eV state density : $N = \Gamma_{\mathrm{spr}}/D \sim 10^5$

$N \sim 10^5 \to 10^2 \sim 10^3$ times enhancement compared with one particle state

Dynamic Enhancement ~10^3 : caused by high level density

Amplification of P-odd asymmetry in p-wave n-A resonance

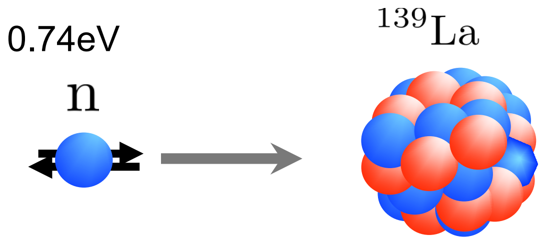


Helicity dependence of the p-p scattering cross section

-(1.7±0.8)×10^{-7} @E=15MeV

$$A_{\mathrm{L}} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-}$$

Interaction between nucleons: 10^{-7} P-violation



Helicity dependence of cross section in neutron transmission ^{139}La (Dubna, Alfimenkov 1982)

0.097±0.003 @E_n=0.74eV

Compound nucleus: 10^{-1} P-violation

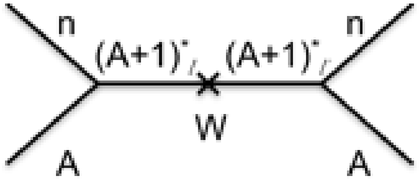
P-odd amplitude can be enhanced by ~10^6 in compound nucleus. Measured more than 40 years ago.

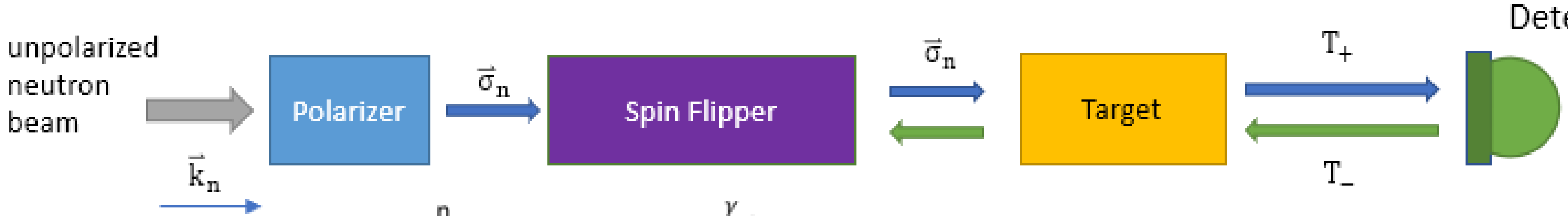
Parity-odd Asymmetry Measurement Methods

Two method for PV measurements

$\vec{\sigma}_n$: neutron spin
$\vec{k}_n$: neutron momentum

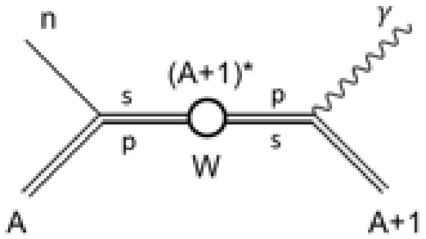
n transmission :

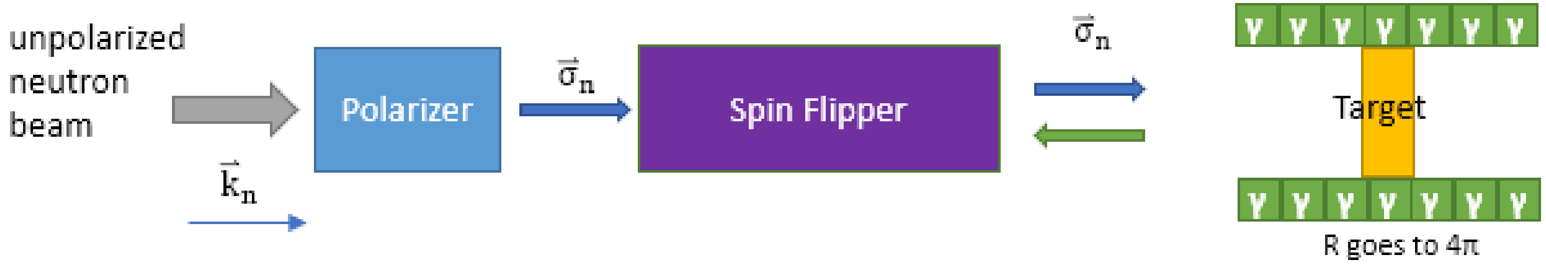




$$A_L = \frac{T_+ - T_-}{T_+ + T_-}$$

(n, γ) :

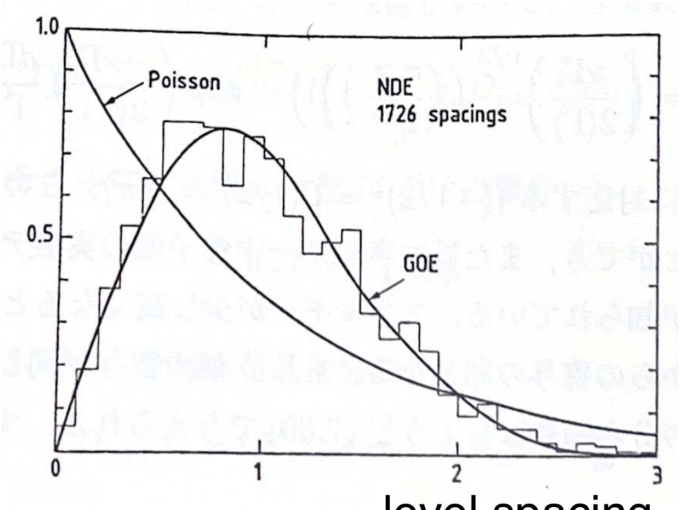




$$A_{L,\gamma} = \frac{R_+ - R_-}{R_+ + R_-}$$

Relations with quantum chaos

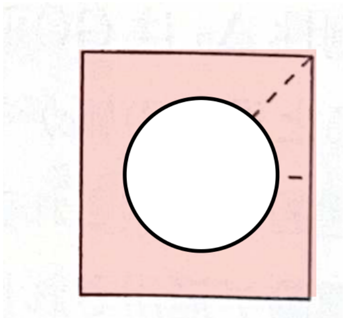
Level spacing of compound resonance



level spacing

- Level repelling was observed
- Consistent with GOE (Gaussian orthogonal ensemble i.e. random matrix: statistical nature)

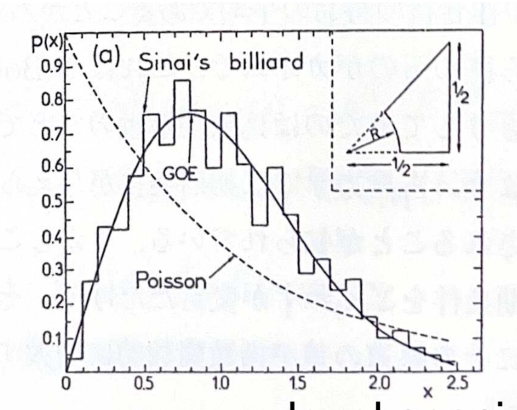
Level spacing of quantum chaos system



Eigenvalues of the the wave function in the Sinai billiard potential

$$(\Delta + k_n^2)\psi_n = 0$$

Potential of Sinai billiard



level spacing

Level spacing of eigenvalues obeys GOE calculation

Ideas of random matrix theory were used as assumptions in TRIPLE analysis of parity violation

(1) Understand P violation in heavy nuclei

-Quantify mean square weak matrix element <M^2> in heavy nuclei

-Compare with statistical theory of P violation in heavy nuclei

- The TRIPLE collaboration calls the many-body parity non-conserving matrix element variance M^2:

$$M^2 = \overline{|\langle\psi_s|V_{pnc}|\psi_p\rangle|^2} - \overline{|\langle\psi_s|V_{pnc}|\psi_p\rangle|}^2$$

Horizontal (A): Mass number of the compound nucleus whose parity–violating asymmetry was measured (from A ≈ 40 up to A ≈ 240).

vertical (Γ_w in 10^{-7} eV): The weak spreading width extracted for that nucleus by the TRIPLE collaboration

$$\frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{\Delta\sigma_{\mathrm{P}}}{2\sigma} = -\frac{2W}{E_{\mathrm{p}} - E_{\mathrm{s}}}\sqrt{\frac{\Gamma^{\mathrm{n}}_{\mathrm{s}}}{\Gamma^{\mathrm{n}}_{\mathrm{p}}}}\sqrt{\frac{\Gamma^{\mathrm{n}}_{\mathrm{p},j=\frac{1}{2}}}{\Gamma^{\mathrm{n}}_{\mathrm{p}}}}$$

W=<s|V$_{pnc}$|p>= P-odd weak mixing amplitude

232 G.E. Mitchell et al. / Physics Reports 354 (2001) 157–241

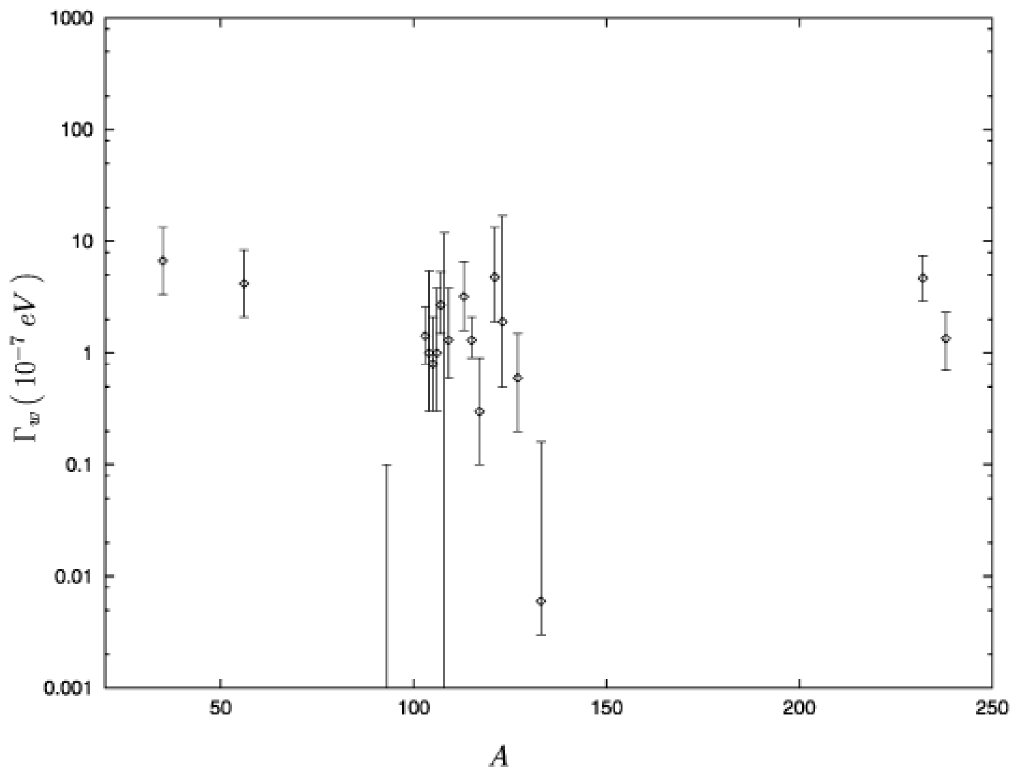
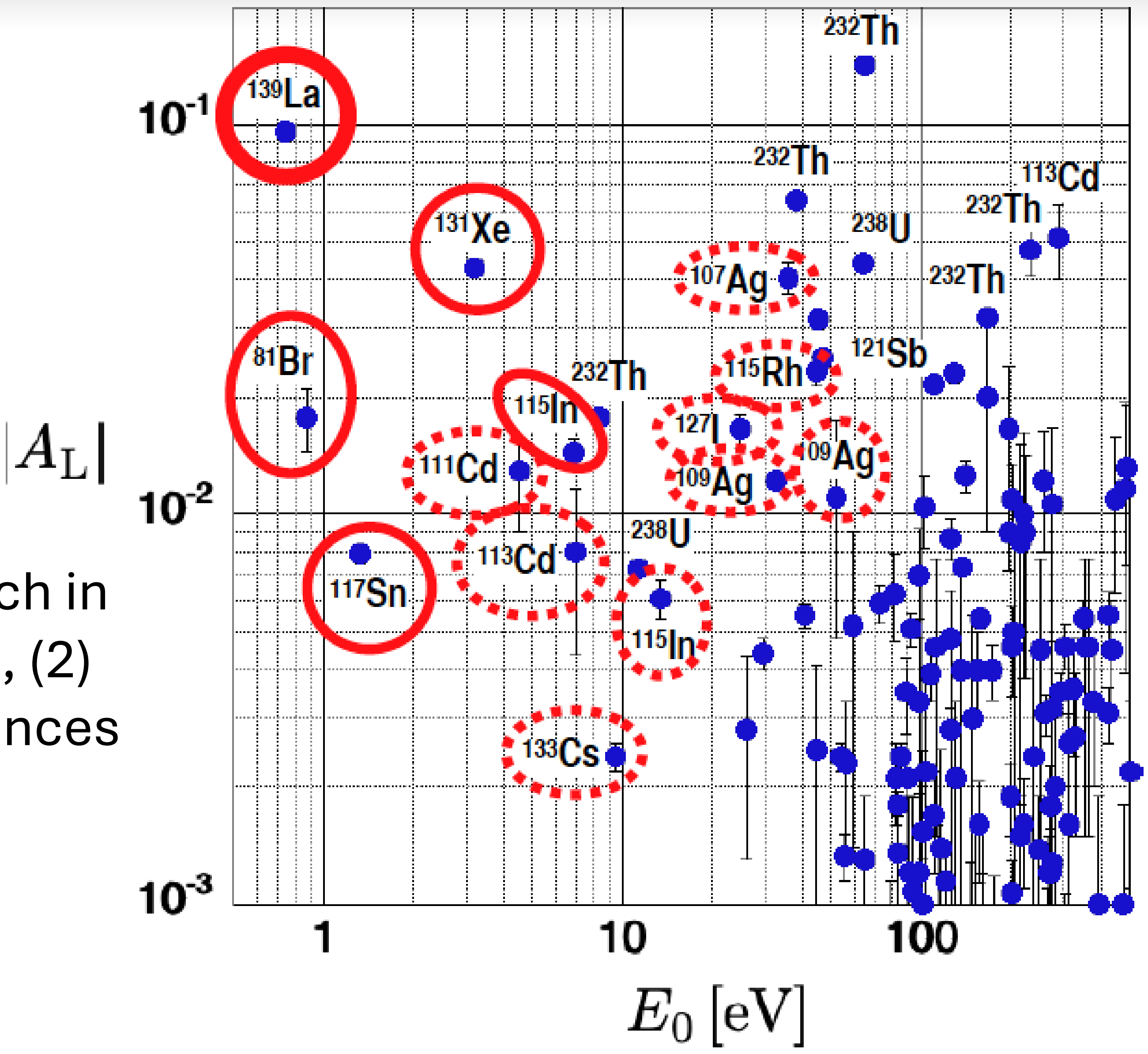


Fig. 17. TRIPLE results for weak spreading widths Γ_w versus mass number in the region $A = 90 - 238$.

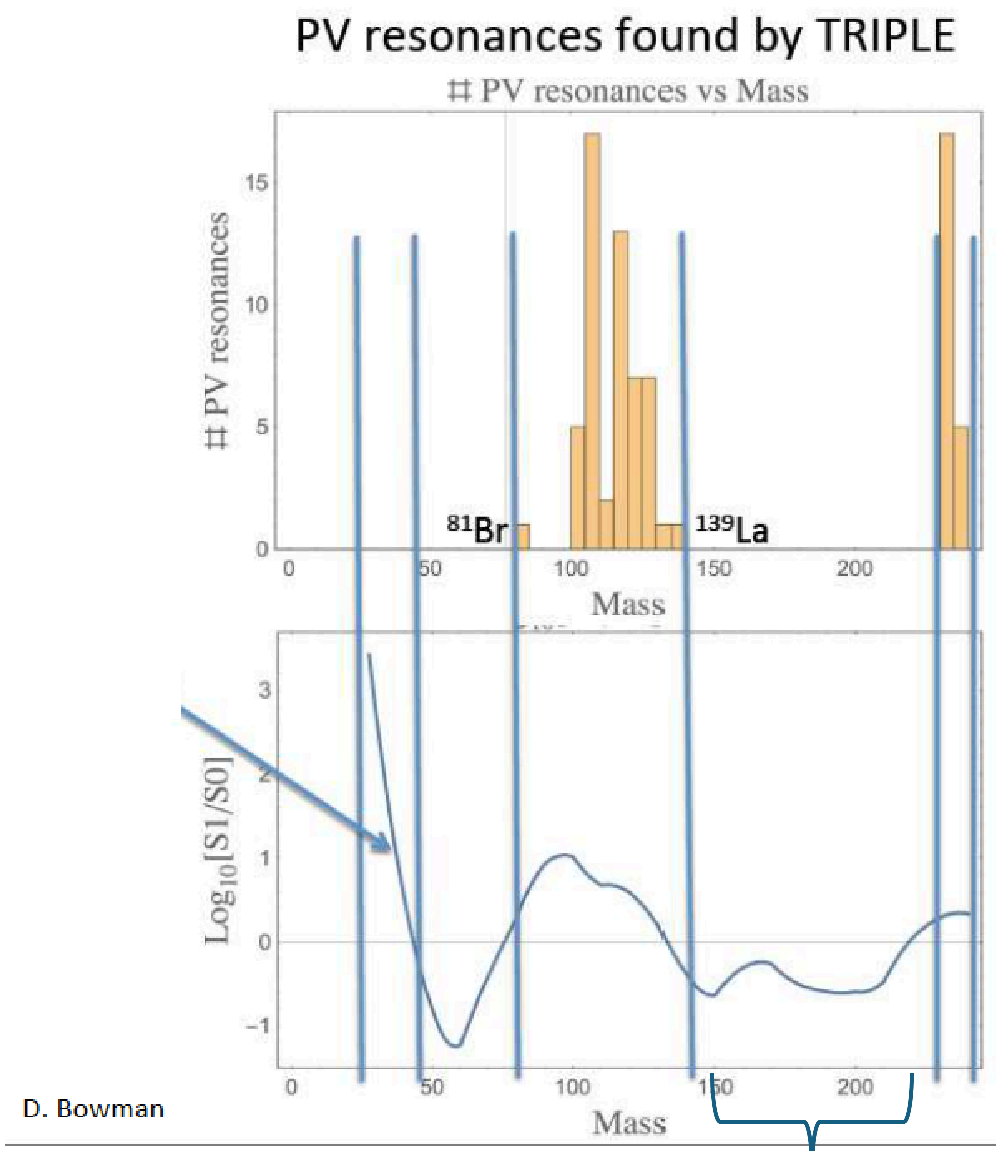
Mitchell, Phys. Rep. 354 (2001) 157
Shimizu, Nucl. Phys. A552 (1993) 293

Measured P-odd asymmetries in n-A resonances



We want to (1) search in unmeasured nuclei, (2) make use of resonances for T

PV search in 140<A<200 nuclei



PV resonances occur If S1/S0 is between 1/3 and 10. The best TRIPLE resonances Have S1/S0 ~ 1

S0 – s-wave neutron strength function
S1 – p-wave neutron strength function

Neutron strength function is proportional to number of resonances per unit energy range at neutron separation (E=0) threshold.

What about 140<A<180?
No data!

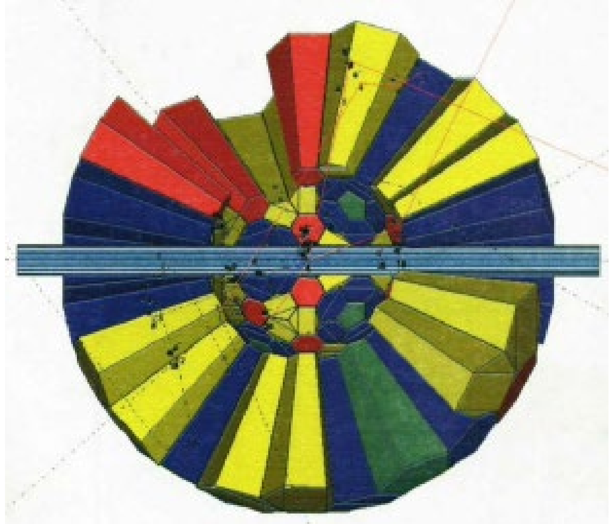
S1/S0 not so different from ^{139}La, ^{81}Br, ^{131}Xe

It only takes one discovery to be useful for NOPTREX

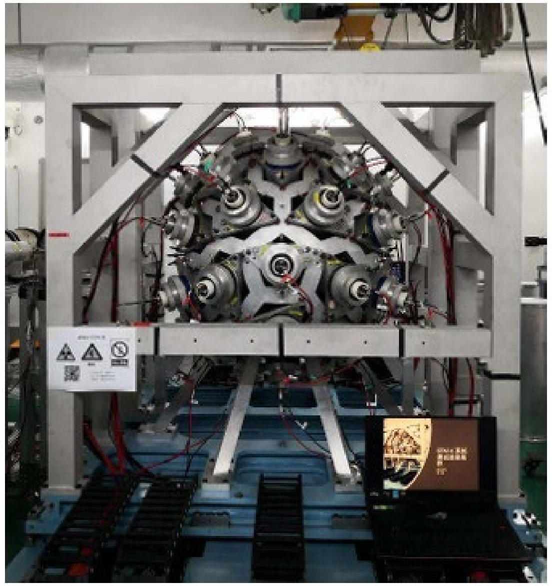
many I>0 nuclei in this range

We are searching here. Initial data taken on 50 nuclei! Part of JPARC Long-Term Proposal award

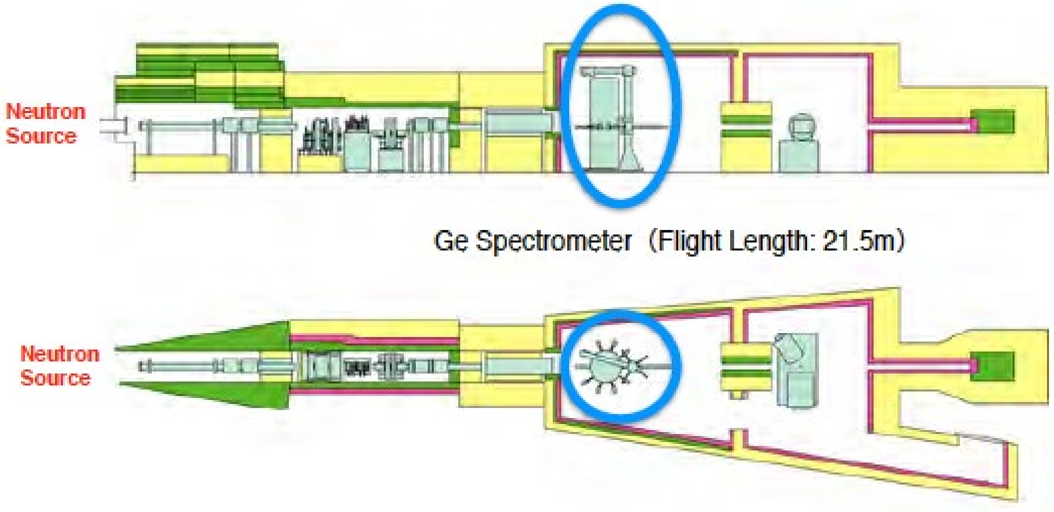
(n, γ) resonance spectroscopy (LANSCE, CSNS, JPARC,…?)



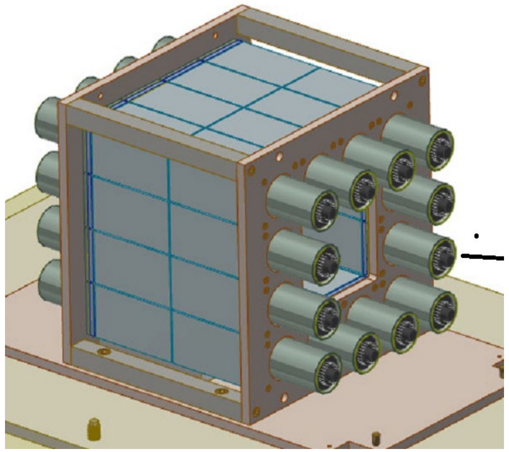
DANCE (BaF2, Los Alamos)



GTAF-2 (BaF2, CSNS)



ANNRI (Ge, JPARC)



FP12 (NaI(Tl), Los Alamos)

Errors on <M²> are dominated by poor knowledge of resonance quantum numbers (L, S, J)

25 years after TRIPLE work, world now has higher neutron flux and many new (n, γ) spectrometers

JPARC Long-Term Proposal beamtime award in progress for this work

Goal (2): P-odd/T-odd

$$D(\vec{s}\cdot[\vec{k}\times\vec{I}])$$

Optical theorem relates forward scattering cross section to spin dependent part of cross section: $\Delta\sigma_p = \frac{4\pi}{k} Im(f_- - f_+)$

Optical theorem relating forward scattering cross section to spin dependent part with a polarized target: $\Delta\sigma_{PT} = \frac{4\pi}{k} Im(f_\uparrow - f_\downarrow)$

For case of 2-resonance mixing:
w_{TP}: P-odd weak mixing matrix element
w: P-odd/T-odd weak mixing matrix element

$$\frac{\Delta\sigma_{PT}}{\Delta\sigma_P} = \kappa(J,\varphi)\frac{w_{TP}}{w}$$

- **κ** function of resonance widths and spins (recently measured for ^{139}La!)

$$\kappa(J,\phi) = \frac{2(J+\frac{1}{2})}{(2J+1)} sin\, 2\phi \qquad \tan\phi = \sqrt{\frac{\Gamma_p^{n,+}}{\Gamma_p^{n,-}}}$$

Forward Scattering Amplitude

$$\sigma_{tot} = \frac{4\pi}{k}\,\mathrm{Im}[f(0)]$$

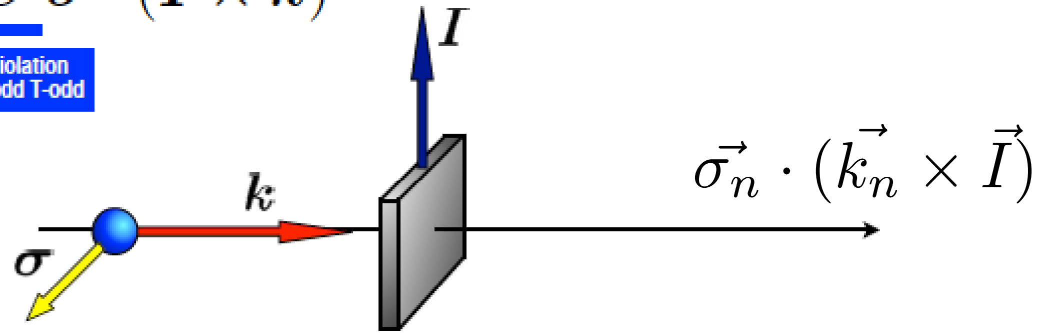
$$f = A' + B'\boldsymbol{\sigma}\cdot\hat{\boldsymbol{I}} + C'\boldsymbol{\sigma}\cdot\hat{\boldsymbol{k}} + D'\boldsymbol{\sigma}\cdot(\hat{\boldsymbol{I}}\times\hat{\boldsymbol{k}})$$

Spin Independent P-even T-even

Spin Dependent P-even T-even

P-violation P-odd T-even

T-violation P-odd T-odd



$|s\rangle$ $J_s E_s \Gamma_s \Gamma_s^n$ $|p\rangle$ $J_p E_p \Gamma_p \Gamma_p^n$ $|p_{1/2}\rangle$ $\Gamma^n_{p,1/2}$ $|p_{3/2}\rangle$ $\Gamma^n_{p,3/2}$ $\langle W\rangle$

The enhancement of P-odd/T-odd amplitude on p-wave resonance (σ.[*K* X *I*]) is (almost) the same as for P-odd amplitude (σ.*K*).

Experimental observable: ratio of P-odd/T-odd to P-odd amplitudes

$$\lambda_{PT} = \frac{\delta\sigma_{PT}}{\delta\sigma_P}$$

λ can now be measured with a stat. uncertainty of ~10^{-6} in 10^7 sec at MW-class spallation neutron sources.

For 10^6 p-wave resonance amplification, T-odd amplitude in nucleon/strong amplitude)~10^{-12}

~10X more sensitive than present limits from neutron/nuclei EDMs

For updated EDM limits and its implications, see Degenkolb et al, : arXiv:2403.02052v1 [hep-ph] 4 Mar 2024

Expressions for λ_{PT} from different BSM sources

$$\frac{W_{TP}}{W} = 0.12|\eta_n| = |(-1.2 g_s \bar{g}_0 + 6.0 g_s \bar{g}_1 + 2.4 g_s \bar{g}_2) 10^5|.$$

where g_s=(strong) pion coupling,
g_0, g_1, g_2 are P-odd/T-odd pion couplings for I=0,1,2

$$\frac{W_{TP}}{W} = 5.3 \times 10^4 |\theta|$$ in terms of θ_{QCD}

$$\frac{W_{TP}}{W} = |(-1.0(\tilde{d}_u + \tilde{d}_d) + 24(\tilde{d}_u - \tilde{d}_d)) 10^{20}|/\mathrm{cm}$$ in terms of quark chromo-EDMs

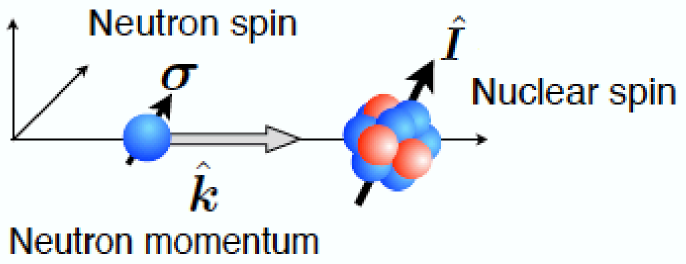
$$\frac{W_{TP}}{W} < 10^{-5}$$ present limit from EDM experiments

V. V. Flambaum and A. J. Mansour, Phys. Rev. C 105, 015501 (2022).
P. Fadeev and V. V. Flambaum, Phys. Rev. C 100 (2019).
N. Yamanaka, B. K. Sahoo, N. Yoshinaga, T. Sato, K. Asahi, and B. P. Das, Eur. Phys. J. A 53, 54 (2017).
S. Mantry, M. Pitschmann, and M. J. Ramsey-Musolf, Phys. Rev. D 90, 054016 (2014).
Y. V. Stadnik, V. A. Dzuba, and V. V. Flambaum, Phys. Rev. Lett. 120, 013202 (2018).

(1) Search for P-odd/T-odd NN interaction

-polarized ^{139}La+polarized n, Phase 1/Phase 2 (JPARC)

- **Phase 1 : T-violation search with parallel spins**

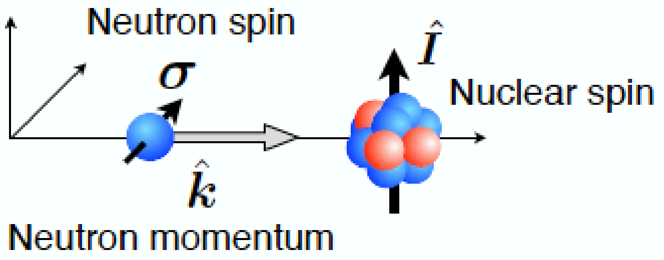


Neutron spin and nuclear spin : Parallel

- Low T-violation sensitivity
- Easy neutron spin transport
- Existing beamline

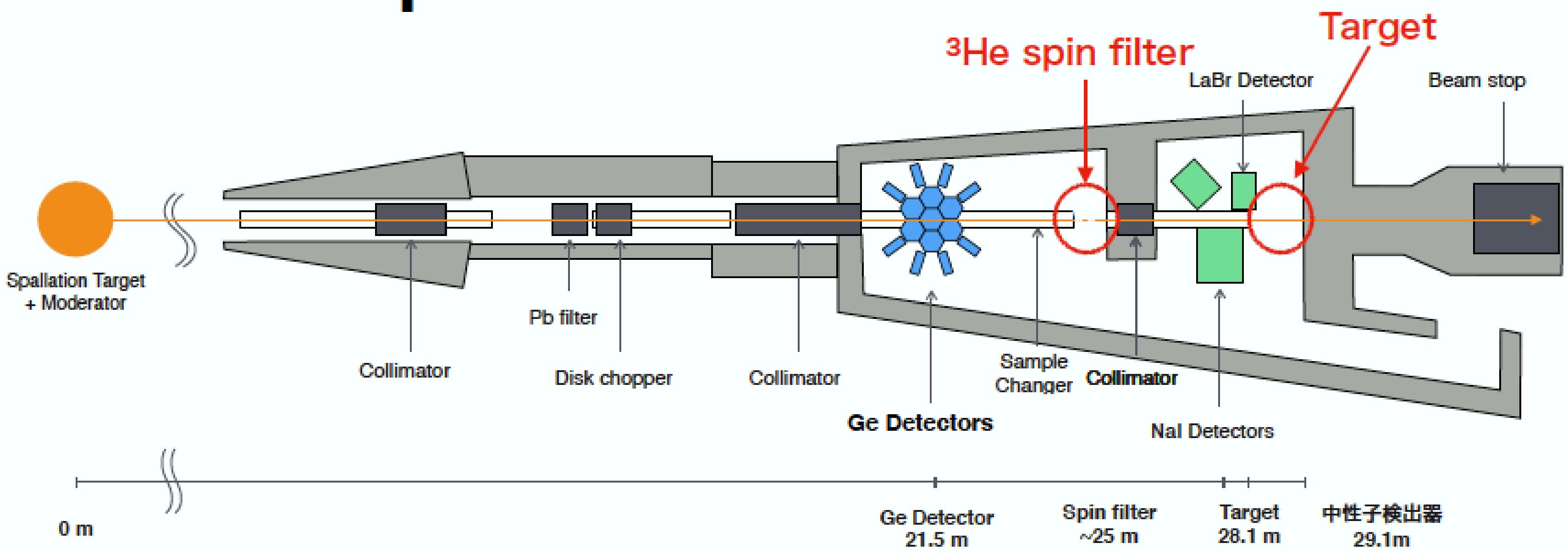
→KEK Program Advisory Committee Stage1 approval

- **Phase 2 : T-violation search with perpendicular spins**

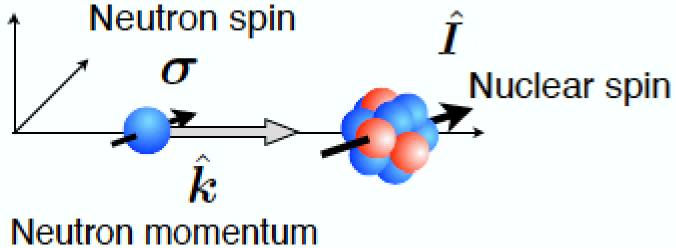


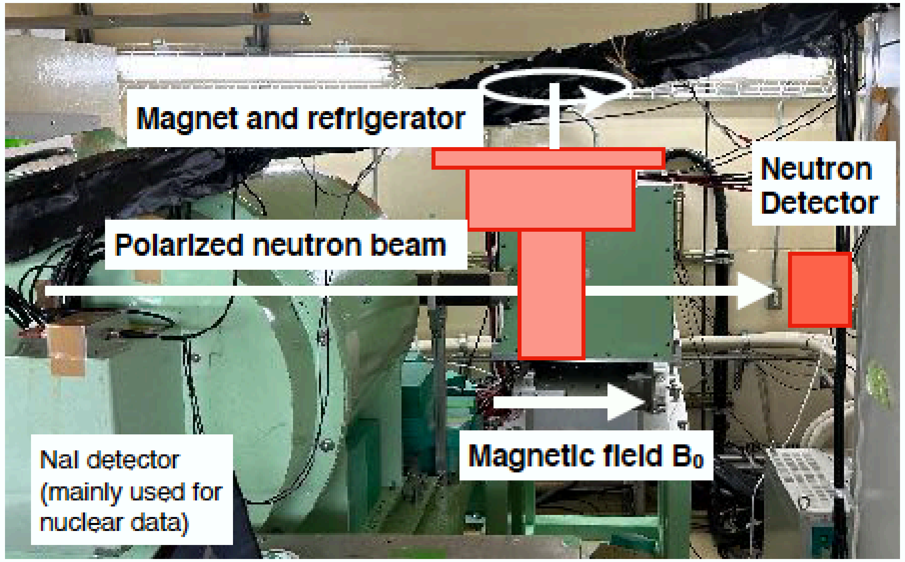
- High T-violation sensitivity
- Difficult neutron spin transport
- Dedicated beamline

Phase 1 experiment : Beamline



in preparation
for the ANNRI
beamline at JPARC





Goal (3): P-even/T-odd

$$F(\vec{k}\cdot\vec{I})(\vec{s}\cdot[\vec{k}\times\vec{I}])$$

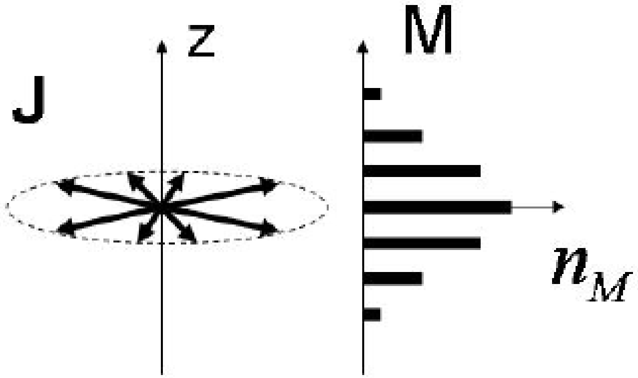
- Mixes two different p resonances. Operator in F term is a rank 2 tensor, so Wigner–Eckart theorem is satisfied
- T reversal acts on channel spins S = I ± ½, so we need two p resonances with different S. Denote them |p1⟩ and |p2⟩ with energies $E_{1,2}$.
- For P-even/TRIV off-diagonal matrix element $w_T \equiv \langle p1|\, V_T\, |p2\rangle$ the cross-section difference is:

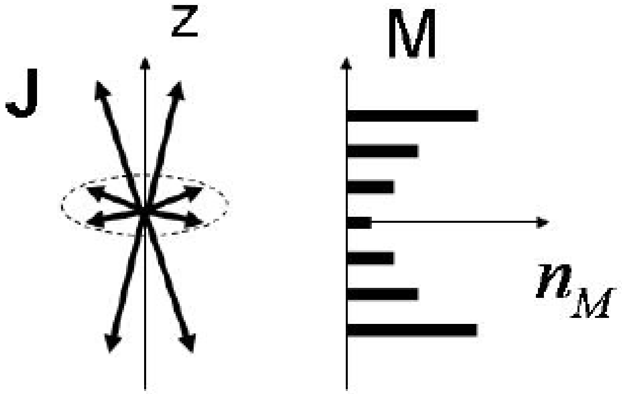
$$\Delta\sigma_T(E_1) \simeq \frac{4\pi}{k^2}\frac{\sqrt{\Gamma^n_{p_1}\Gamma^n_{p_2}}}{(E_1-E_2)}\frac{w_T}{E_1-E_2}\,\frac{(E_1-E_2)^2}{(E_1-E_2)^2+\frac{1}{4}(\Gamma_{p_1}+\Gamma_{p_2})^2}$$

- No structural enhancement: “only” 10^3 complexity enhancement

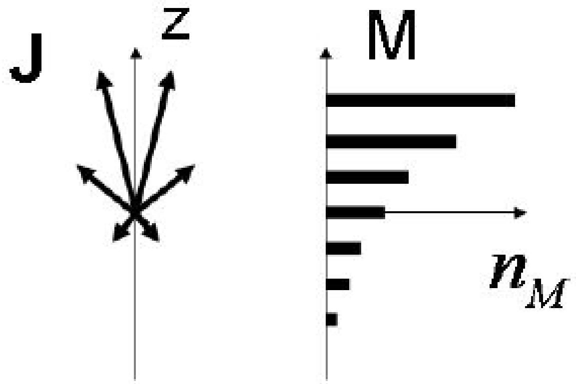
Polarization and Alignment $F(\vec{k}\cdot\vec{I})(\vec{s}\cdot[\vec{k}\times\vec{I}])$

Alignment: $p_2(J) = \dfrac{3\langle M^2\rangle - J(J+1)}{J(2J-1)}$





Polarization:



$p_1(J) = \dfrac{\langle M\rangle}{J}$

F term is a **rank-2 irreducible tensor built from two copies of the target-spin vector** $\mathbf{I}$

Clebsch–Gordan coupling of two rank-1 tensors (the spherical components of $\mathbf{I}$):

$$T_q^{(2)}(\mathbf{I},\mathbf{I}) \;=\; \left[\mathbf{I}\otimes\mathbf{I}\right]_q^{(2)} \;=\; \sum_{m_1,m_2=-1}^{+1} \langle 1\,m_1,\;1\,m_2\,|\,2\,q\rangle\, I_{m_1}\, I_{m_2}$$

quadrupole order: spins prefer the z but may point both up and down equally (think of a cigar vs. a pancake distribution)

Can be created in deformed nuclei with a large electric quadrupole moment acted on with a crystal-generated electric field at low T

What About P-even/T-odd NN?

No P-even/T-odd effects in Standard Model: CKM, $\boldsymbol{\theta}$ both P-odd/T-odd

Lowest mass meson exchange from $\boldsymbol{\rho}^{+/-}$ [C-odd, J≥1]

[Herczeg Nucl. Phys. **75**, 655 (1966), Simonius PLB **58**, 147 (1975)]

VERY few experiments:

Charge symm. breaking [Simonius PRL **78**, 4161(1997)]: $g_\rho<7\times10^{-3}$

N transmission aligned Holmium (P. R. Huffman et al, PRC 55, 2684 (1997): $\boxed{g_\rho<6\times10^{-2}}$

Comparing with EDM P-odd/T-odd: $\boxed{g_\pi<10^{-11}}$

Direct constraints on P-even/T-odd NN interactions are poor

Y. Uzikov

Three scientific goals of NOPTREX: **Present Status**

(1) Understand P violation in heavy nuclei

-New p-wave resonances in 140<A< 200: data taken, under analysis

-Ongoing (n, γ) spectroscopy for TRIPLE data reanalysis

(2) Search for P-odd/T-odd nA interaction

-Phase 1 approval at JPARC! Building apparatus, ^{139}La polarized to >35% by dynamic nuclear polarization

(3) Search for P-even/T-odd nA interaction

-Cryogenic R & D work in China for tensor alignment in ^{127}I crystal. Experiment planned for Chinese Spallation Neutron Source (CSNS)

Thanks!

Hamiltonian for s–p mixing

Take a pure s resonance $|s\rangle$ at E_s and a p resonance $|p\rangle$ at E_p with widths $\Gamma_{s,p}$. The weak parity-violating nucleon–nucleon force introduces a real mixing matrix element $v \equiv \langle s| V_{PV} |p\rangle$.

$$H = \begin{pmatrix} E_s - i\Gamma_s/2 & v \\ v & E_p - i\Gamma_p/2 \end{pmatrix}$$

Expand the T-matrix to first order in v: $T_{fi}^{(1)} = \sum_{\alpha,\beta=s,p} \langle f| V_\alpha |\alpha\rangle \frac{1}{E - E_\alpha + i\Gamma_\alpha/2} v_{\alpha\beta} \frac{1}{E - E_\beta + i\Gamma_\beta/2} \langle\beta| V_\beta^\dagger |i\rangle$

where $V_{s,p}$ couple the neutron to the compound levels. At $E \approx E_p$ only the chain $|i\rangle \to |s\rangle \to |p\rangle \to |f\rangle$ is resonant.

Helicity-dependent total cross section: $\Delta\sigma_P(E_p) = \frac{4\pi}{k^2} \frac{\sqrt{\Gamma_s^n \Gamma_p^n}}{\Gamma_p} \frac{v}{E_p - E_s} \frac{(E_p - E_s)^2}{(E_p - E_s)^2 + \frac{1}{4}(\Gamma_s + \Gamma_p)^2}$

THEORY OF T-VIOLATING P-CONSERVING EFFECTS IN NEUTRON-INDUCED REACTIONS

V.P. GUDKOV

Leningrad Nuclear Physics Institute, Gatchina, Leningrad 188350, USSR

Received 10 January 1990
(Revised 25 July 1990)

Forward transmission ⇒ null test for T violation
Enhancement of asymmetry from high level density~10^3

P-even/T-odd NN interactions can mix different p-wave resonances

$$\Delta\sigma_T = \frac{4\pi}{k}\,\mathrm{Im}\,\{\Delta f_T\}$$

$$\Delta\sigma_T \simeq \frac{4\pi}{k^2}\frac{\langle\tilde{\Gamma}^n_p\rangle v_T}{[p_1][p_2]}\{(E-E_{p1})\Gamma_{p2}+(E-E_{p2})\Gamma_{p1}\}$$

where $iv_T = \langle\varphi_{p2}|\hat{V}_T|\varphi_{p1}\rangle$;

$$\langle\tilde{\Gamma}^n_p\rangle = (\Gamma^n_{p1}(-)\Gamma^n_{p2}(+))^{1/2} - (\Gamma^n_{p1}(+)\Gamma^n_{p2}(-))^{1/2};$$

Γ_p (+) and Γ_p (-) = Γ_p (J=I±½)

$$\underset{\text{total angular momenta}}{J} = \underbrace{\overset{\text{orbit}}{\ell} + \overset{\text{n spin}}{s}}_{\text{n entrance spin } j} + \overset{\text{nuclear spin}}{I}, \qquad \underbrace{s + I}_{S \text{ channel spin}}$$

$$P : |\ell s I\rangle \to (-1)^{\ell} |\ell s I\rangle$$

$$\ell = 0,1$$

$$\Downarrow$$

P-odd ⇒ s-wave and p-wave interference

$$T : |\ell s I\rangle \to (-1)^{i\pi S} K |\ell s I\rangle$$

$$S = I \pm 1/2$$

$$\Downarrow$$

T-odd ⇒ channel spin S interference

κ(J) “Spectroscopy” Factor

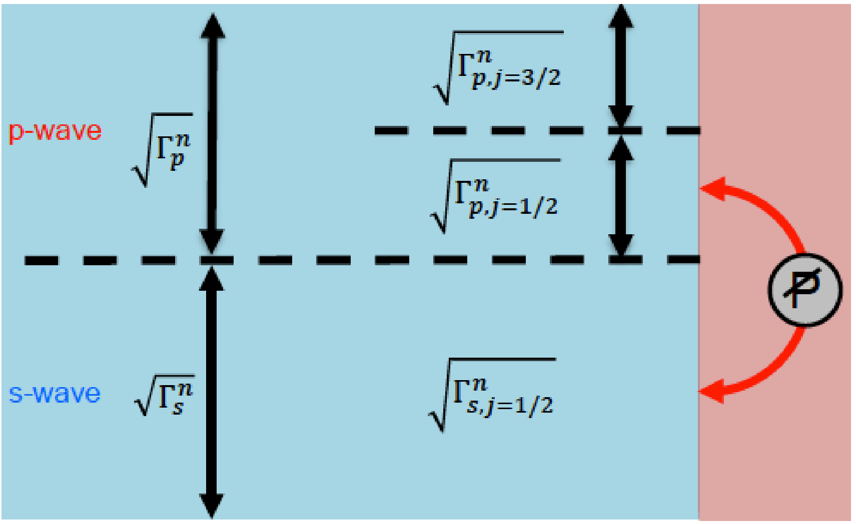
P transformation acts on L=0,1 T transformation acts on S=I +/- 1/2

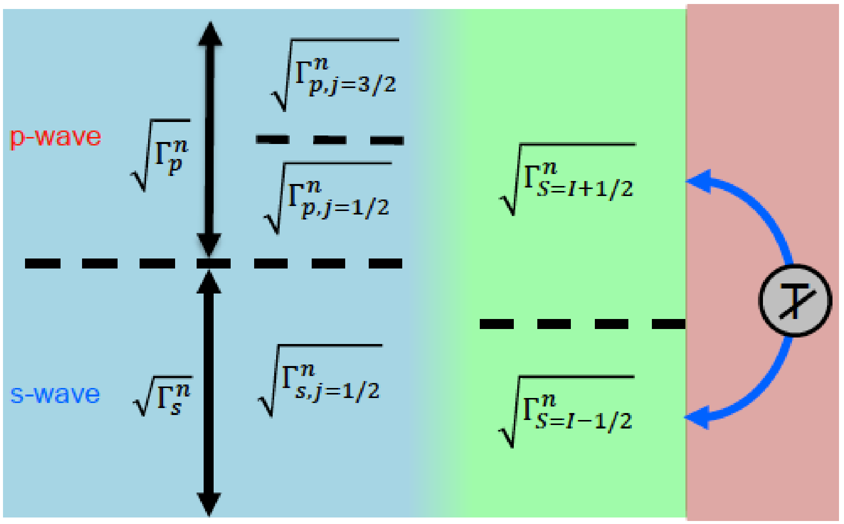
$$P : |\ell s I\rangle \rightarrow (-1)^{\ell} |\ell s I\rangle$$

$$\ell = 0,1$$

$$T : |\ell s I\rangle \rightarrow (-1)^{i\pi S} K |\ell s I\rangle$$

$$S = I \pm 1/2$$





$$\kappa(J = I + 1/2) = \left[\frac{\sqrt{I}}{2I+1}\right]\left(-2\sqrt{I} + \sqrt{2I+3}\,\frac{y}{x}\right)$$

$$\kappa(J = I - 1/2) = \left[\frac{1}{2\sqrt{2I+1}}\right]\left(2\sqrt{I+1} + \sqrt{2I-1}\,\frac{y}{x}\right)$$

Spin-weighted linear combination of p-wave resonance widths in the j=1/2 and j=3/2 channels

Must be measured

P-odd Asymmetries on p-wave Neutron Resonances

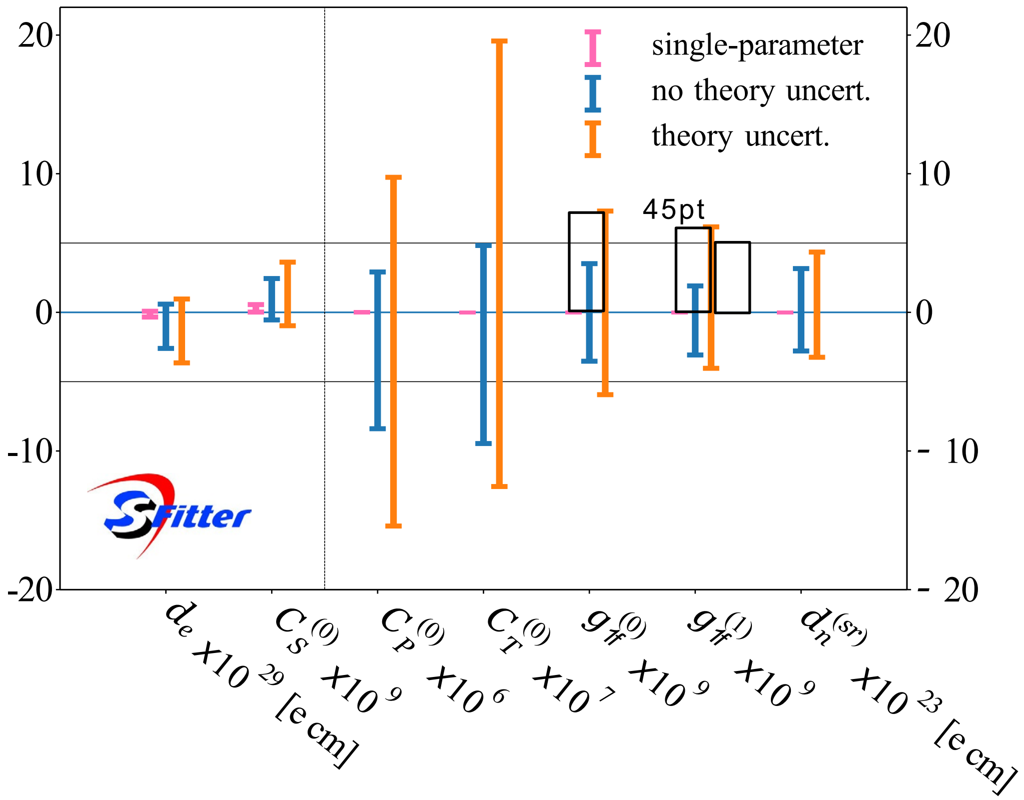
Parity violations observed by TRIPLE

Target	Reference	All	$p+$	$p-$
^{81}Br	[67]	1	1	0
^{93}Nb	[125]	0	0	0
^{103}Rh	[132]	4	3	1
^{107}Ag	[97]	8	5	3
^{109}Ag	[97]	4	2	2
^{104}Pd	[134]	1	0	1
^{105}Pd	[134]	3	3	0
^{106}Pd	[43,134]	2	0	2
^{108}Pd	[43,134]	0	0	0
^{113}Cd	[121]	2	2	0
^{115}In	[136]	9	5	4
^{117}Sn	[133]	4	2	2
^{121}Sb	[101]	5	3	2
^{123}Sb	[101]	1	0	1
^{127}I	[101]	7	5	2
^{131}Xe	[140]	1	0	1
^{133}Cs	[126]	1	1	0
^{139}La	[152]	1	1	0
^{232}Th below 250 eV	[135]	10	10	0
^{232}Th above 250 eV	[127]	6	2	4
^{238}U	[41]	5	3	2
Total		75	48	27
Total excluding Th		59	36	23

Measured P-odd asymmetries in n-A resonances >3σ

Similar #s of + and – asymmetries, as expected in statistical model

G. E. Mitchell, J. D. Bowman, S. I Penttila, E. I. Sharapov, Phys. Rep. **354**, 1 (2001).



38pt=5

$g_\pi^{(1)} < 5.9 \times 10^{-9}$

$g_\pi^{(2)} < 6.8 \times 10^{-9}$

SciPost Physics Submission

A Global View of the EDM Landscape

Skyler Degenkolb[1], Nina Elmer[2],
Tanmoy Modak[2], Margarete Mühlleitner[3], and Tilman Plehn[2,4]

1 Physikalisches Institut, Universität Heidelberg, Germany
2 Institut für Theoretische Physik, Universität Heidelberg, Germany
3 Institute for Theoretical Physics, Karlsruhe Institute of Technology, Karlsruhe, Germany
4 Interdisciplinary Center for Scientific Computing (IWR), Universität Heidelberg, Germany

Abstract

Permanent electric dipole moments (EDMs) are sensitive probes of the symmetry structure of elementary particles, which in turn is closely tied to the baryon asymmetry in the universe. A meaningful interpretation framework for EDM measurements has to be based on effective quantum field theory. We interpret the measurements performed to date in terms of a hadronic-scale Lagrangian, using the SFitter global analysis framework. We find that part of this Lagrangian is constrained very well, while some of the parameters suffer from too few high-precision measurements. Theory uncertainties lead to weaker model constraints, but can be controlled within the global analysis.

Beyond-the-Standard-Model (BSM) operators

- Each Observable in NOPTREX corresponds to BSM operator.

1 PV Observable $(\boldsymbol{\sigma}\cdot\hat{\mathbf{k}})$

1. *Hadronic level:* $\mathcal{L}_{\rm PV} = h_\pi^1\,\bar{N}\tau^3\pi N + h_\rho^{0,1}\,\bar{N}\rho_\mu N + \ldots$
2. *SMEFT parents:* $\mathcal{O}_{Hud} = i(\tilde{H}^\dagger D_\mu H)\,\bar{u}_R\gamma^\mu d_R$, plus four-quark $(V{-}A)$
3. *Example UV:* heavy W' gauge boson, scalar leptoquarks.

2 PVTV Observable $\boldsymbol{\sigma}\cdot(\hat{\mathbf{k}}\times\mathbf{I})$

1. $\mathcal{L}_{\rm PVTV} = \bar{g}_\pi^{0,1,2}\,\bar{N}\tau^i\pi^i N + \ldots$
2. Parents: quark chromo-EDM $\tilde{d}_q\,\bar{q}\sigma^{\mu\nu}T^aG_{\mu\nu}\gamma_5 q$, three-gluon (Wein
$w\,G\tilde{G}G$.
3. UV: QCD θ term, SUSY with complex A-terms, etc.

3 PCT Observable $(\boldsymbol{\sigma}\cdot\mathbf{I})(\hat{\mathbf{k}}\cdot\mathbf{I})$

1. $\mathcal{L}_{\rm PCT} = g_\rho^T\,\bar{N}\sigma^{\mu\nu}\tau^3 N\,\partial_\mu\rho_\nu + \ldots$
2. Parents: parity-conserving but CP-odd four-quark $(\bar{q}\gamma_\mu q)(\bar{q}\gamma^\mu\gamma_5 q)$.
3. UV: left–right symmetric models (W_R exchange), some vector leptoq

Back up slides

κ(J) uncertainties — Measured with (n, γ) angular distributions at ANNRI; current value κ = 0.9 ± 0.1 in ^{139}La.

Question	20-sec answer
How do you avoid final-state interactions mimicking T?	Forward transmission has identical in/out states ⇒ by CPT, any fake phase is P-even. Null-test proven by Ryudin (1964) and Gudkov & Bowman (2014).
What about unknown resonance phases?	Ratio $\Delta\sigma^{PT}/\Delta\sigma^{P}$ cancels strong-phase uncertainty; statistical theory error < 3 %.
Lattice input?	Needed only to translate null into
Tensor alignment feasibility?	^127I, ^121Sb: EQM ≈ 800 mb, align to $P_2 \simeq 0.3$ at 50 mK; cryo hardware exists (YES crystals).
Pseudomagnetic precession systematics?	Monitored with in-beam neutron spin-echo; $<10^{-7}$ phase control already demonstrated in ^3He cell tests.